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Identification of aeroelastic forces on twin bridge cables from full-scale measurements in skewed winds

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1 ABSTRACT

Despite much research in recent years, large amplitude vibrations of inclined bridge cables continue to be of concern. Various mechanisms for the excitation have been suggested, including rain-wind excitation, dry inclined cable galloping, high reduced-velocity vortex shedding and excitation from the deck and/or towers.

Since 2010, the Technical University of Denmark has been monitoring the vibrations of the twin inclined cables of the Øresund Bridge. From the acquired data, Georgakis and Acampora [1] showed that the cable aerodynamic damping can be determined for wind orthogonal to the twin cables, in dry and wet conditions. In parallel, Acampora et al. [2] showed for the same cables that both coupled and uncoupled aeroelastic forces can be determined from the monitoring data, again when the wind is orthogonal to the cable and in dry conditions. In an expansion of the previous work, the aim of this paper is to identify the aeroelastic forces for in-plane and out-of-plane vibrations of bridge cables in dry conditions as in [2], but now for skewed winds. To achieve this, an output-only system identification employing the Eigenvalue Realisation Algorithm (ERA) [3] has been applied to selected vibration events. From this, the effective stiffness and damping matrices (including aeroelastic effects) have been identified from the cable vibrations.

2 INTRODUCTION

Large amplitude wind-induced vibrations of inclined cables are common. Various mechanisms could be responsible, including von Kármán vortex shedding, rain-wind excitation, cable-deck-tower interaction and dry inclined cable galloping. The aerodynamic mechanisms acting on inclined cables are complicated by the three-dimensional environment and the fact that typical sized bridge cable stays in moderate to strong winds sit in the critical Reynolds number region, where there is a rapid drop in the drag coefficient and potentially changes in the lift coefficient. Large wind-induced vibrations of inclined cables have been observed with a long-term full-scale measurement system on the Fred Hartman Bridge [4]. It was observed that the three-dimensional nature of the cable-wind environment affects the mechanisms associated with the vibrations of inclined cables. Macdonald [5] measured the aerodynamic damping of cables on the Second Severn Crossing, which was found to be dominant over the structural damping, even in light winds for low frequency modes. On the Øresund Bridge, large amplitude cable vibrations have been reported, both in the presence of ice on the cables and in warmer conditions [6]. Recently a long-term monitoring system has been installed and vibrations under rain-wind conditions have been reported [1]. In the present paper, the measurements obtained from the Øresund Bridge monitoring system have been used to estimate the total stiffness and damping matrices for the first and second mode of Cable 8M, the longest cable monitored without a damper, for a range of wind velocities from 2 to 15m/s in dry conditions for relative wind to cable plane angles β of 0°, 10°, 30°, 45° and 70°.

3 BRIDGE AND MONITORING SYSTEM

The current investigation is based on data obtained from the monitoring system on the Øresund Bridge. The bridge has a main span of 490 m and an orientation of WNW to ESE. The deck carries both road and rail traffic and is supported by 4 independent 204 m tall pylons, and by 80 parallel double-stays. All of the stays have an inclination of 30° to the horizontal plane and are arranged in a harp-shaped configuration (Fig.2). Each double-stay is made up of a pair of cables, arranged vertically with a centre-to-centre distance of three diameters and with rigid connections between the two cables in each pair at one or two locations along the length. The cables comprise multiple seven-wire mono-strands within HDPE tubes, all with the same outer diameter of 250 mm and with double helical fillets on the surface. Radial dampers are installed in the anchorages of the

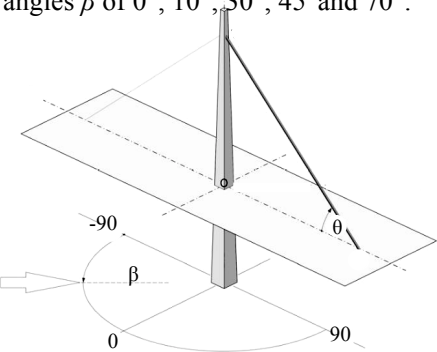


Figure 1: Relative wind angle β

The cables comprise multiple seven-wire mono-strands within HDPE tubes, all with the same outer diameter of 250 mm and with double helical fillets on the surface. Radial dampers are installed in the anchorages of the

longest cables. Accelerometers are oriented to record the components of the cable vibrations normal to the cable axis in the in-plane (i.e. in the vertical plane) and out-of-plane (i.e. lateral) directions. Ultrasonic anemometers are positioned at the top of the east pylon (on a 4 m pole) and on the deck (on the south side on poles 7 m above the deck) at mid-span and between the shortest two pairs of cables west of the east pylon (Fig. 1). A rain gauge is positioned on the top of the pylon. Further data collected include atmospheric humidity, temperature, and pressure. All channels are acquired at a frequency of 30 Hz and saved in files of 10 minutes length. The double-stay studied in this paper is Cable 8M, on the windward side of the deck, the third longest stay in the main span with a length of 216m and a mass per unit length of 99kg/m. The data were collected continuously between January and December 2011.

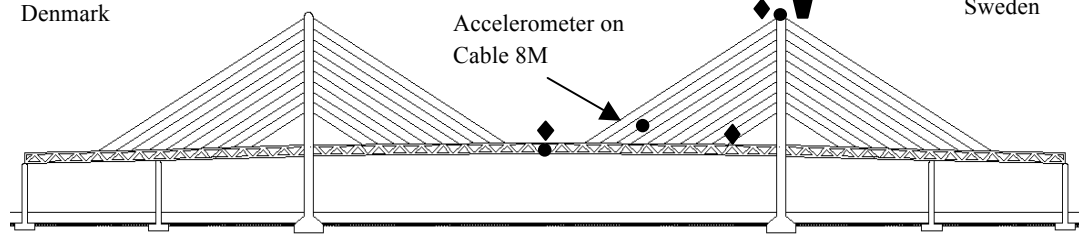


Figure 2. Instruments and monitored cables: ● accelerometer, ◆ anemometer and ▼ rain-gauge.

4 SYSTEM IDENTIFICATION

The aim is to identify the damping and stiffness matrices of the cable as a function of wind velocity for different relative wind angles β ($10^\circ \pm 5^\circ$, $30^\circ \pm 5^\circ$, $45^\circ \pm 5^\circ$, $70^\circ \pm 5^\circ$, see Fig. 1) and to compare them with the values obtained for relative wind angles $\beta = 0^\circ \pm 5^\circ$ (normal to cable pairs) [2] in dry conditions. This results in 378, 205, 235 and 291 records of 10-minutes length, respectively, distributed over wind speeds from 2-15m/s (using the mean of the measured wind speeds at the top of the pylon and on the deck at mid-span). The cable exhibits vibrations in multiple modes. The focus here is on the local cable vibrations and, for simplicity, one mode in each plane is considered at a time. Therefore the raw accelerations were filtered with 15th order high-pass and low-pass filters to isolate the single mode in each plane, taking care not to distort the signal. The filtered signals are considered as the response of a translational 2DOF system. It is assumed that there is no coupling with the other cable modes at different frequencies [6]. The equations of motion of the 2-DOF system (assumed linear) can be written in the form:

$$\begin{bmatrix} \ddot{X} \\ \ddot{Y} \end{bmatrix} + \frac{\mathbf{C}}{M} \begin{bmatrix} \dot{X} \\ \dot{Y} \end{bmatrix} + \frac{\mathbf{K}}{M} \begin{bmatrix} X \\ Y \end{bmatrix} = \frac{1}{M} \begin{bmatrix} F_X \\ F_Y \end{bmatrix} \quad (1) \quad \mathbf{K} = \begin{bmatrix} K_{XX} & K_{XY} \\ K_{YX} & K_{YY} \end{bmatrix} = \mathbf{K}_s + \mathbf{K}_a \quad (2) \quad \mathbf{K}_s = \begin{bmatrix} M\omega_{X,i}^2 & 0 \\ 0 & M\omega_{Y,i}^2 \end{bmatrix} \quad (3)$$

where, M is the generalised mass (assumed to be the same for vibrations in each plane), X and Y are respectively the out-of-plane and in-plane generalised displacements, dots represent derivatives with respect to time, and F_X and F_Y are the external generalised forces in the two planes due to wind and cable end motion. \mathbf{K} is the total stiffness matrix, given by the sum of the structural, \mathbf{K}_s , and the aerodynamic stiffness matrix, \mathbf{K}_a . \mathbf{C} is the total damping matrix, given by the sum of the structural, \mathbf{C}_s , and aerodynamic part, \mathbf{C}_a :

$$\mathbf{C} = \begin{bmatrix} C_{XX} & C_{XY} \\ C_{YX} & C_{YY} \end{bmatrix} = \mathbf{C}_s + \mathbf{C}_a \quad (4) \quad \mathbf{C}_s = \begin{bmatrix} 2M\omega_{X,i} \zeta_{X,i} & 0 \\ 0 & 2M\omega_{Y,i} \zeta_{Y,i} \end{bmatrix} \quad (5)$$

where, $\omega_{X,i}$ and $\omega_{Y,i}$ are respectively the circular natural frequencies of the i th out-of-plane and in-plane modes of the cable (in the absence of wind), and $\zeta_{X,i}$ and $\zeta_{Y,i}$ are the corresponding structural damping ratios. From output-only measurements alone it is possible to identify \mathbf{C}/M and \mathbf{K}/M . The accelerations were analyzed with a system identification procedure based on ERA. The method assumes the external loading to be white noise and that the system is linear (including the aeroelastic forces, modelled as linear functions of cable displacement and velocity). The maximum lag length of the covariance functions used for the ERA method was optimised as 54s, based on the minimum value of the standard deviation of the results for multiple records at comparable wind speeds.

5 RESULTS AND DISCUSSION

Figures 3, 4 and 5 present the results of the system identification as mean values of the terms of the total stiffness and aerodynamic damping matrices divided by the modal mass, \mathbf{K}/M and \mathbf{C}/M respectively, for the relative cable-wind angles $\beta = 0^\circ$, 10° , 30° , 45° and 70° for the first and second mode of Cable 8M. Each point represents the mean of the results from all records within a 1m/s range. The terms of the

stiffness matrices (Fig. 3) show well defined values with little variation with wind speed and no significant variation with wind to cable direction β for the first and second mode. The natural frequencies in the two planes (from the square roots of the diagonal terms) are near identical and they are close to a harmonic series (shown by the factor of 4 in the diagonal terms between the first and second modes), as expected for a taut cable. The off-diagonal terms of the stiffness matrix have near zero values for all wind directions. The terms of the aerodynamic damping matrices are shown in Figures 4 and 5 for the first and second mode, respectively. There are clear trends with wind speed, indicating aerodynamic damping for the diagonal terms of the two matrices. The diagonal terms of the aerodynamic damping matrices show linear trends, compatible with conventional quasi-steady theory [7], up to around 7 m/s, i.e. $Re = 1.2 \times 10^5$, which can be considered as the end of the sub-critical Reynolds number region. From static wind tunnel tests, Kleissl and Georgakis [8] found that the critical Reynolds number region for a single inclined cable with double helical fillet corresponds to a range of about $0.8-1.3 \times 10^5$. In Figs. 4 and 5 the maximum value of C_{xx}/M corresponds to damping ratios of approximately 0.34% for mode 1 and 0.17% for mode 2. In Figs. 4 and 5 there appears to be little influence of the wind direction, β . The minimum aerodynamic damping in both planes occurs at around 13-15 m/s ($Re = 2.2-2.5 \times 10^5$), but within the range of wind speeds with data available it is still positive, indicating there is not an aerodynamic instability of the cable in these conditions, in agreement with the observation of no large amplitude vibrations. The off-diagonal terms of the damping matrix are virtually zero for all the considered wind directions. It is notable that the first and second modes give very similar results, despite their different natural frequencies, hence reduced velocities. This is clear evidence that the drop in aerodynamic damping is governed by the Reynolds number rather than the reduced velocity.

6 CONCLUSIONS

The analysis shows that cable aerodynamic force coefficients for skewed wind directions can be well identified for in-plane and out-of-plane vibrations. There is negligible effect of aeroelastic stiffness. However there are clear trends in the diagonal terms of the damping matrix indicating aerodynamic damping. These trends with wind speed are very similar for the first and second modes, with different frequencies hence reduced velocities. This gives clear evidence that the behaviour is governed by Reynolds number rather than the reduced velocity. The aerodynamic damping is linearly related to the wind speed in the sub-critical Reynolds number region, but shows a drop (though not becoming negative) in the critical Reynolds number range. The off-diagonal terms of the stiffness and damping matrices appear to show no significant aeroelastic coupling between the two planes for the cases investigated.

7 ACKNOWLEDGMENTS

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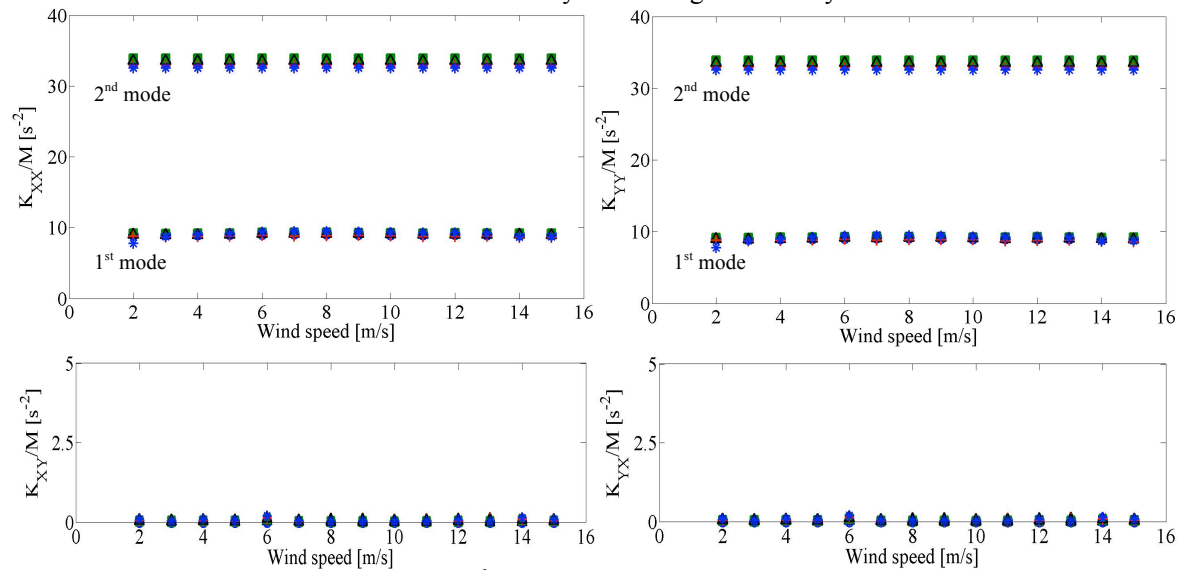


Figure 3. Stiffness matrices for 1st and 2nd mode pairs for wind direction $\beta = 0^\circ$ (blue circle), 10° (green square), 30° (black triangle), 45° (blue star) and 70° (red cross) for first and second mode (second mode values are linked with dashed line in the off-diagonal terms).

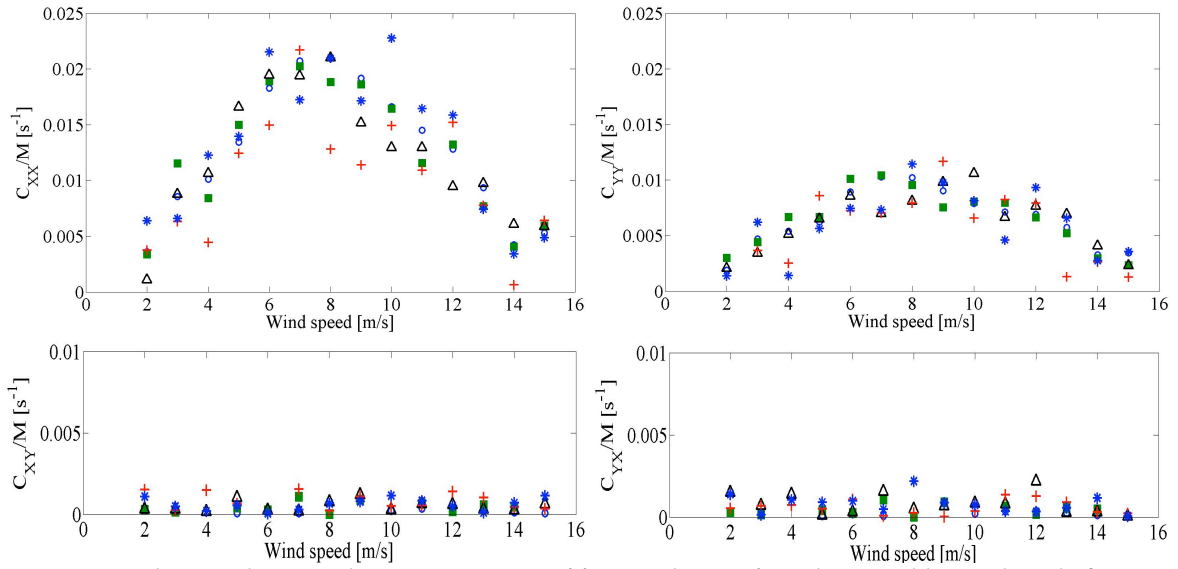


Figure 4. The aerodynamic damping matrices of first mode pair for relative cable-wind angle $\beta = 0^\circ$ (blue circle), 10° (green square), 30° (black triangle), 45° (blue star) and 70° (red cross).

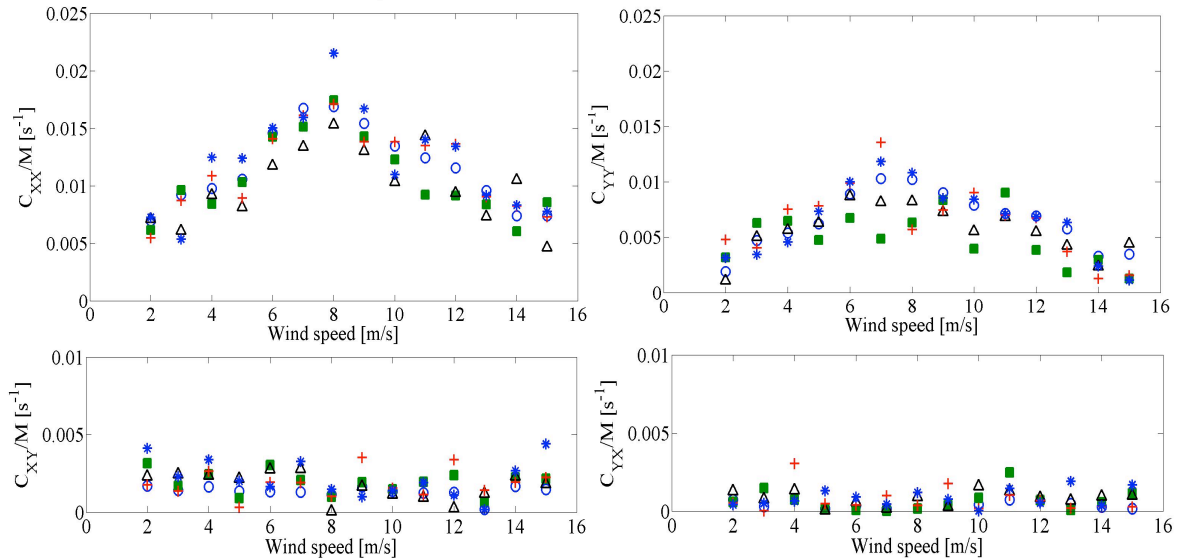


Figure 5. The aerodynamic damping matrices of second mode pair for relative cable-wind angle $\beta = 0^\circ$ (blue circle), 10° (green square), 30° (black triangle), 45° (blue star) and 70° (red cross).

8 REFERENCES

- [1] Georgakis, C.T., Acampora, A., "Determination of the aerodynamic damping of dry and wet bridge cables from full-scale monitoring", ISCD 2011, Shanghai, China.
- [2] A. Acampora, J.H.G. Macdonald, C.T. Georgakis, "Identification of aeroelastic forces on bridge cables from full-scale measurements", EVACES 2011, Varenna, Italy.
- [3] J.B. Jakobsen, E. Hjorth-Hansen 1995, "Determination of the aerodynamic derivatives by a system identification method", J. Wind Eng. Ind. Aerodyn., 57(2-3), 295-305.
- [4] Zuo D., Jones N.P., 2010, "Interpretation of field observations of wind- and rain-wind-induced stay cable vibrations", J. Wind Eng. Ind. Aerodyn., 98, 73-87.
- [5] J.H.G. Macdonald, 2002, "Separation of the contributions of aerodynamic and structural damping in vibrations of inclined cables", J. Wind Eng. and Ind. Aerodyn. 90, 19-39.
- [6] B.Svensson, L.Emanuelsson, E. Svensson, 2004, "Øresund Bridge – Cable system – Vibration incidents, mechanisms and alleviating measures", Proc. 4th Int. Cable Supported Bridge Operators' Conference, Copenhagen, 16-19 June, 99-108
- [7] J.H.G. Macdonald, G.L. Larose, 2008, "Two-degree-of-freedom inclined cable galloping-Part 1: General formulation and solution for perfectly tuned system", J. Wind Eng. Ind. Aerodyn. 96, 291-307
- [8] K.Kleissl, C.T. Georgakis, 2012, "Comparison of the aerodynamics of bridge cables with helical fillets and a pattern-indented surface", J. Wind Eng. and Ind. Aerodyn. 104-106, 166-175.